Effect of saturable absorption on the behavior of spontaneous emission in semiconductor lasers

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A substantial reduction of the spontaneous emission intensity is observed at the onset of stimulated emission in some injection lasers. It is shown that this effect is caused by the saturation of optically absorbing traps present in the active region. It is suggested that saturable optical absorption is also responsible for previously unexplained similar reduction observed by Nicoll in bulk semiconductor lasers.

A decrease of the spontaneous emission associated with the onset of lasing in semiconductors pumped optically or by electron beam was observed by Nicoll.[1] He reported that no explanation for the phenomenon could be found in the framework of presently accepted theories. In the present letter, we show that saturable absorption can account for the observed reduction. This was done by studying the behavior of junction lasers which have the onset of lasing governed by saturable absorbing traps.

Junction lasers have been shown to contain trapping centers which above a certain transition temperature produce a long delay between the beginning of the excitation and the onset of stimulated emission.[2-6] In the same region of temperature where the delays are produced, the traps have been shown to be saturable absorbers[3-8] which can be filled either by capture of an injected electron from the conduction band or by photon-assisted capture of an electron from the valence band.[3-5] This latter behavior allows the traps to be rapidly saturated at the onset of stimulated emission.[5,9-10]

To study the effects of absorption saturation on the spontaneous emission, we chose a single-heterostructure laser[11-12] in which the traps represent a substantial proportion of the total loss of the laser.[13] The laser was excited with 120-nsec (1-kHz repetition rate) current pulses at 77 °K,[14] and the light was observed through a double monochromator with a cooled C 31034 RCA photomultiplier, as described earlier.[15-16] This system allowed the observation of the time development of the radiation of the laser at any wavelength. Using a 500-Ω resistor as a load for the photomultiplier and a 7704 Tektronix oscilloscope, a time resolution of about 4 nsec was obtained.

In Fig. 1, we show the time behavior of the laser emission at two different wavelengths as excitation current is increased. In the top trace, we see the intensity (on an inverted scale) of the emission at the lasing line (7916 Å).[17] As the current is increased, the delay between the start of the current pulse and onset of stimulated emission is reduced as expected.[3-6] Turning the

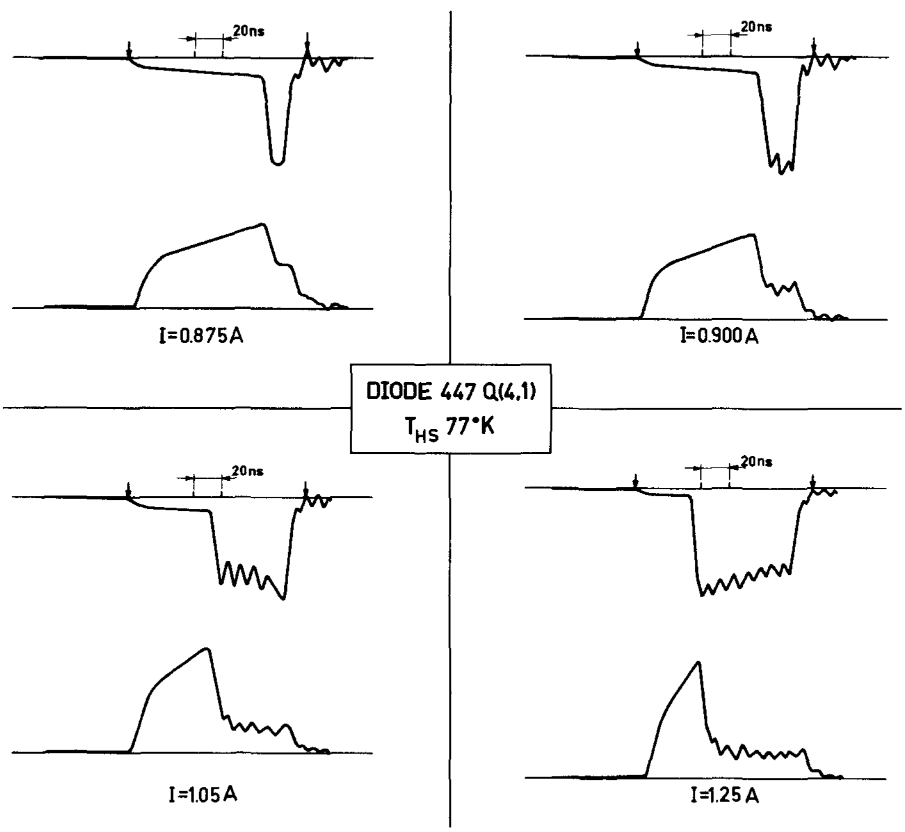

FIG. 1. Time behavior of emission of a laser at two wavelengths for several injection levels. The top trace in each drawing shows the intensity (on an inverted scale) of the lasing wavelength (7916 Å), while the bottom trace shows the spontaneous emission at a frequency higher than of the lasing line (7860 Å). Arrows indicate beginning and end of the 120-nsec (1-kHz repetition rate) current pulse. The large reduction of the spontaneous emission at the onset of lasing should be noted in each case. The threshold current was $I_{th} = 0.850$ A.

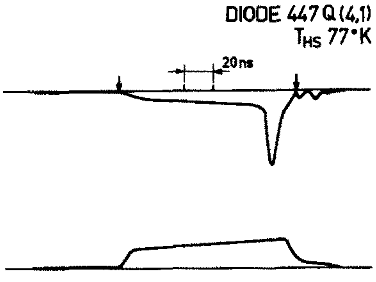

FIG. 2. Time behavior of spontaneous emission at a wavelength higher than the lasing line (7990 Å). A tracing at the lasing wavelength (7916 Å) is shown on top for reference. In contrast with what is shown in Fig. 1, no reduction of the spontaneous emission at this wavelength is observed.

spectrometer to a slightly higher frequency (7860 Å), we observe in all cases a very strong drop in the spontaneous emission level (lower trace in Fig. 1). Similar drop was observed for all frequencies above the lasing frequency. This behavior is analogous to Nicoll's observations in bulk semiconductor lasers.[1] At frequencies lower than the laser line, little if any drop was observed (Fig. 2).

The experiment just described shows that the saturation of the absorbing traps can lead to a reduction of the spontaneous emission in spite of the fact that the absorption is reduced, contrary to the conclusion of Ref. 1. Although a detailed theory cannot be published in a letter, this can be understood from simple terms: As the traps are saturated, the losses for the lasing line are reduced; equilibrium is only reached when the gain is also lowered toequal the losses. This is accomplished by a decrease of the stimulated emission lifetime and a consequent reduction in the number of carriers in equilibrium in the active region even though the rate of injection (current density) remains constant. Since the spontaneous emission rate is proportional to the number of carriers in equilibruim, it will also be reduced. If the injected electrons are in thermal equilibrium among themselves, the reduction in gain will correspond to a lowering of the quasi-Fermi level, which explains why the reduction is mostly felt on the high-energy side of the lasing line since the low-energy side of the spontaneous emission is contributed mostly by states which are below the new position of the quasi-Fermi level.

This interpretation is confirmed first by the fact that as the current is increased, as shown in Fig. 1, the ultimate level of the spontaneous emission decreases further, which indicates that the larger saturation of traps by the increased stimulated light led to a lower gain and consequently a lower spontaneous emission. Another confirmation is taken from a comparison of the spectra of the spontaneous emission taken before and after the onset of lasing with the help of a boxcar integrator. The total spontaneous emission is reduced by the saturation of traps in the way expected (reduction of the high-energy side). It is interesting to note that lasing is not observed near the peak of the original spontaneous emission curve (7870 Å) but near its peak after the traps are saturated (7916 Å). It is quite possible that lasing actually starts near the former peak but shifts rapidly to the latter as the traps are saturated and the gain reduced. This shift, however, must occur, if it does, within a time scale comparable with the stimulated emission lifetime, which is well beyond the time resolution of our equipment.

The laser we chose for this letter is the one which shows the biggest reduction in spontaneous emission of all lasers tested. Using lasers in which the trap-related absorption accounts for a smaller fraction of the total laser loss, qualitatively similar, but much smaller, effects were observed. In particular, for homostructure lasers at room temperature the effect was barely detectable. On short-delay lasers in which the traps are not active, no effect was observed. In conclusion, we have shown that a substantial reduction of the spontaneous emission at the onset of stimulated emission can occur in semiconductor lasers because of saturable absorption. It is suggested that this may also be the explanation for the observations of Nicoll.[1] In his case, the saturable absorption is probably provided by regions within the cavity that are not completely pumped, which is caused by the inherent inhomogeneity of the pumping process (optical and electron beam) he used. This possibility could be tested by using a two-contact diode like ones described by Lasher and by Lee and Roldan.[13-19] Since we do not have this type of diode available to us, we could not do the experiment ourselves.

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